DIESEL-CNG DUAL FUEL COMBUSTION CHARACTERIZATION USING VIBRO-ACOUSTIC ANALYSIS AND RESPONSE SURFACE METHODOLOGY

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A thesis submitted in fulfillment of the requirement for the award of the
Doctor of Philosophy of Mechanical Engineering

Faculty of Mechanical and Manufacturing Engineering
Universiti Tun Hussein Onn Malaysia

SEPTEMBER 2019

ACKNOWLEDGEMENT

ٱلْحَمْدُ للهِ to Allah Almighty for His blessing and guidance. To Prophet Muhammad, peace and blessing be upon him.

I would like to express my deepest gratitude and appreciation to my dear and beloved wife Siti Suhana Binti Jamaian, also my lovely kids (Faheem Irsyad, Fayyadh Ifwat, Faathir Ilman, and Farhaa Ilyeen). I am really cherished your tremendous support and prayers that always be the backbone and driving force for me to complete this thesis. Not forgotten to my family members, especially my beloved parents, Zulkifli bin Ab. Latiff and Kasjuniar Abdul Rahman for their endless support and prayers.

My thanks extend to everyone involved in completing this project, especially to my supervisor, Assoc. Prof. Dr Mas Fawzi bin Mohd Ali for his supervision and encouragement throughout my PhD project journey. I also would like to convey my special thanks to my co. supervisor, Dr Shahrul Azmir Bin Osman who has never failed to give me advice and supports to complete my study.

Warmful thanks to Mr Muammar Mukhsin Bin Ismail, Mr Mzahar bin Abd. Jalal, Mr Mustakim Bin Tukiman, Mr Putera Mohamad Adam bin Amat Azman, Dr Norrizal Bin Mustaffa and Dr Rais Hanizam bin Madon for providing guidance and helping me on the equipment and instrumentation setup for experimental work. Special thanks to Universiti Tun Hussein Onn Malaysia for providing funding and facilities such as laboratories, equipment, and library access to accommodate this research work.

ABSTRACT

Engine conversion process from any diesel vehicle to a diesel-CNG dual fuel system requires additional fuel management. The need for an engine monitoring is vital to ensure the dual fuel operation run smoothly without excessive knocking, which may shorten the life of the engine. Knock and air-fuel ratio (AFR) sensors are commonly used for engine monitoring during fuel management setup. However, the engine output characteristics has been overlooked during the monitoring process. This study is aimed to explore a statistical approach by predicting the relationship between fuel management and engine output characteristics of diesel-CNG dual fuel engine using Response Surface Methodology (RSM). Two inputs which are CNG substitution rate and engine speed were used to predict the engine output characteristics in terms of engine performance, exhaust emissions, combustion pattern and combustion stability. Within the investigation, a statistical method was proposed to analyse the vibro-acoustic signal generated by a knock sensor installed at the outer cylinder wall of the engine. The frequency distribution analysis was applied to interpret the high variability of the vibro-acoustic signal. The results were used as the input for combustion stability in RSM analysis. It also provided useful information with regards to the engine stability. The response surface analysis showed that the CNG substitution rate and its properties significantly influenced the engine output characteristics. This study also describes the methodology to determine the accuracy and the significance of the developed prediction models. The prediction models were validated using confirmation test and showed good predictability within 95% confidence interval. Thus, it is concluded that RSM provide models that predict the engine characteristics with significant accuracy, which contributes to the effectiveness of diesel-CNG dual fuel engine conversion process.

ABSTRAK

Proses penukaran enjin dari mana-mana kenderaan diesel kepada sistem dwi bahan bakar diesel-CNG memerlukan pengurusan bahan bakar tambahan. Keperluan pemantauan enjin adalah penting untuk memastikan operasi dwi bahan api berjalan dengan lancar tanpa *knocking* yang berlebihan, yang boleh memendekkan jangka hayat enjin. Sensor bagi *knock* dan udara-bahan api (AFR) biasanya digunakan untuk pemantauan enjin semasa persediaan pengurusan bahan api. Walau bagaimanapun, ciri-ciri output enjin telah diabaikan semasa proses pemantauan. Kajian ini bertujuan untuk meneroka pendekatan statistik dengan meramalkan hubungan antara pengurusan bahan api dan ciri-ciri output enjin diesel-CNG dwi bahan api menggunakan Metodologi Permukaan Respon (RSM). Dua input iaitu kadar penggantian CNG dan kelajuan enjin digunakan untuk meramalkan ciri output enjin dari segi prestasi enjin, pelepasan ekzos, corak pembakaran dan kestabilan pembakaran. Semasa siasatan, kaedah statistik dicadangkan untuk menganalisis isyarat vibro-akustik yang dihasilkan oleh sensor *knock* yang dipasang di luar dinding silinder enjin. Analisis taburan frekuensi digunakan untuk menafsirkan kebolehubahan tinggi isyarat vibro-akustik. Hasilnya digunakan sebagai input untuk kestabilan pembakaran dalam analisis RSM. Ia juga menyediakan maklumat berguna berkaitan dengan kestabilan enjin. Analisis respon permukaan menunjukkan bahawa kadar penggantian CNG dan sifatnya telah mempengaruhi ciri output enjin. Kajian ini juga menerangkan metodologi untuk menentukan ketepatan dan kepentingan model ramalan yang telah dibangunkan. Model ramalan telah disahkan menggunakan ujian pengesahan dan menunjukkan ramalan yang baik dalam lingkungan 95% selang keyakinan. Oleh itu, disimpulkan bahawa RSM menyediakan model ramalan yang mengawasi ciri-ciri enjin dengan ketepatan yang signifikan, yang menyumbang kepada keberkesanan proses pengubahan enjin dwi bahan bakar diesel-CNG.

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LIST OF SYMBOLS AND ABBREVIATIONS

AFR	Air Fuel Ratio
AI ATDC	Acoustic Index After Top Dead Centre
AI BTDC	Acoustic Index Before Top Dead Centre
ANOVA	Analysis of Variance
AP	Adequate Precision
BMEP	Brake Mean Effective Pressure
BRIC	Band-pass Rectify Integrate Compare
BSEC	Brake Specific Energy Consumption
BTE	Brake Thermal Efficiency
CAD	Crank Angle Degree
CCD	Central Composite Design
CD	Combustion Duration
cDAQ	compact data acquisition
CI	Confidence Interval
CNG	Compressed Natural Gas
CO	Carbon monoxide
CO_2	Carbon dioxide
COV	Coefficient of Variance
CPI	Consumer Pricing Index
CWT	Continuous Wavelet Transform
DAQ	Data acquisition
DDF	Diesel Dual Fuel
df	degree of freedom
DF-PCCI	Dual Fuel Premixed Charge Compression Ignition
DoE	Design of Experiment
ECU	Electronic Control Unit
EGR	Exhaust Gas Recirculation
EOC	End of Combustion

EPA	Environmental Protection Agency
ESC	European Stationary Cycle
EUI	Electronic Unit Injector
FDS	Fraction Design Space
FS	Full Scale
FTP	Federal Test Procedure
GHG	Greenhouse Gas
HC	hydrocarbon
HPDI	High Pressure Direct Injection
HOME	Honge Oil Methyl Ester
HRR	Heat Release Rate
Hz	Hertz
ICA	Independent Component Analysis
ID	Ignition Delay
IMEP	Indicated Mean Effective Pressure
IQR	interquartile range
JPJ	Department of Road Transport Malaysia
LNG	Liquefied Natural Gas
LOF	Lack of Fit
MAF	Mass Air Flow
MIDC	Modified Indian Driving Cycle
MS	Malaysia Standard
NGV	Natural Gas Vehicle
NI	National Instrument
NO_x	nitrogen oxide
OBD	On-Board Diagnosis
OEM	Original Equipment Manufacturer
PME	Palm Methyl Ester
PP	peak in-cylinder pressure
PRESS	predicted residual square error sum
Q1	first quartile
Q3	third quartile
RM	Ringgit Malaysia
RNG	Renewable Natural Gas

ROI	Return On Investment
RON	Research Octane Number
rpm	revolution per minute
RSM	Response Surface Methodology
RSS	Root-Sum-Square
SDP	Symmetrised Dot Pattern
SLPM	standard litre per minute
SOC	Start of Combustion
SOI	Start of Injection
Std. Dev.	Standard Deviation
STFT	Short-Time Fourier Transform
SUV	Sport Utility Vehicle
TDC	Top Dead Centre
THC	total hydrocarbon
VGT	Variable Geometry Turbine
vol	volume
WVD	Wigner-Ville Distribution
4WD	four wheel drive
a	area of bore
a_s	velocity of sound
bp	brake power
B	cylinder bore
CV	Calorific Value
cc	cubic centimetre
CO_2/km	carbon dioxide per kilometre
$f_{u,s}$	oscillation frequency of in-cylinder gas
ft-lb	foot pound force
g	gravity
g/s	gram per second
J/(kg-K)	Joule per kilogram-Kelvin
J/CAD	Joule per crank angle degree
k	ratio of specific heat
K	Kelvin

kg	kilogram
kg/h	kilogram per hour
kg/m^3	kilogram per metre cubic
kJ/kg/K	kiloJoule per kilogram per Kelvin
ks	kilo seconds
kW	kiloWatts
l	Stroke
L	Litre
L/100 km	Litre per 100 kilometre
m	mass
$\dot{m}$	mass flow rate
M	physical parameters
m/s	meter per seconds
m^2	meter square
MJ/kg	mega Joule per kilogram
MJ/kWh	mega Joule per kiloWatts hours
mm	millimetres
mm^2/s	millimetre square per second
MOhm	mega unit of resistance
MPa	mega Pascal
ms	milliseconds
mV/g	milliVolt per gravity
n	number of working stroke per minute
n_e	engine speed
Nm	Newton meter
N_r	number of revolution per engine cycle
^{o}C	degree Celsius
P	pressure
Pa	Pascal
pC	pico Coulomb
ppm	part per million
psia	pound per square inch absolute
R	gas constant of working gas

R^2_{ajd}	adjusted R^2
R^2_{pred}	predicted R^2
rel	relative
R_i	measuring range
R_u	random uncertainty
s	number of nodes in the radial oscillation
S_i	uncertainty in M
S_u	Systematic uncertainty
tscf	trillion standard cubic feet
T	temperature
$U_{overall}$	overall uncertainty
u	number of nodes in the circumferential oscillation
V	Volt
V	volume
X_i	variable
$\rho_{u,s}$	vibration mode factor
γ	specific heat ratio
η_v	volumetric efficiency
θ	crank angle degree
λ	minimum residual sum of squares

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CHAPTER 1

INTRODUCTION

1.1   Background of research

Natural gas is an alternative fuel derived from non-renewable energy source. It has the lowest Greenhouse Gas (GHG) emissions compared to other fossil fuel. According to F. Königsson, natural gas offers 20% reduction in GHG emissions compared to gasoline and diesel because its chemical properties of methane that are larger in hydrogen to carbon ratio [1]. Furthermore, it is inexpensive compared to other fuel and its abundant resource which is sufficient for upcoming decades has appeared as a priority for fossil fuel replacements.

Natural gas can be utilized as Compressed Natural Gas (CNG), Liquefied Natural Gas (LNG) or Renewable Natural Gas (RNG) using retrofitted kits. Retrofitted kits are additional components such as CNG tanks, Electronics Control Unit (ECU), pressure gas regulator, gas injectors and wire harness. These are commonly used for engine conversion into Natural Gas Vehicle (NGV).

Most CNG conversion kits systems for NGV are illustrated in Figure 1.1, which it depends on engine type. For spark ignition engine, it can be converted into either mono-fuel or bi-fuel systems. Meanwhile, for compression ignition engine, either mono-fuel or dual fuel system can be utilized. For mono-fuel systems, the NGV uses 100% CNG, while for bi-fuel systems; the NGV can alternately use 100% CNG or 100% gasoline. In the case of a dual fuel system, α% of CNG is mixed with β% of diesel fuel in the combustion chamber. The CNG is injected through intake manifold; either using the sequential port injection or by the fumigation method. Then it is mixed with air as a homogeneous charge. The homogeneous charge between air and CNG is ignited as it is initiated by diesel fuel combustion during the compression stroke.
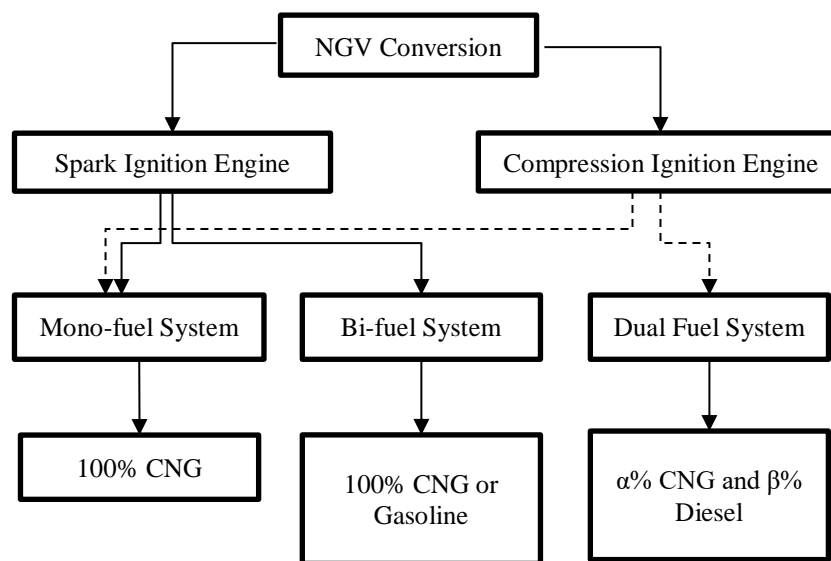
Figure 1.1: CNG fuel system for NGV conversion

According to NGV Global, there is existed about 23 million of NGVs in the world and may exceed 30 million by 2024 [2]. The NGV's market is dominated by passenger cars and its quantity is low compared to gasoline or diesel vehicle. In Europe, the NGV's market is low as 3% [3]. Meanwhile, in Malaysia, the registered NGVs are about 77 thousand compared to 14.68 million for other registered vehicles (cars, public service vehicles, and goods vehicles). This is less than 1% [4, 5]. Despite many efforts have been established in the development of CNG in road transport applications, there is still a barrier need to be addressed in order to enhance the NGV's market [6, 7].

The major obstacle for NGV development is the engine conversion, where it should be the main focus in this research because the availability of the conversion kits is feasible. However, the deployment into the existing vehicles is the key factor [8]. A survey has been conducted to get expert opinions on the NGV's research needed for energy policy development [9]. From the survey, it is noted that the short-term priority for NGV development is on the NGV and refuelling infrastructure. It means that the integration and test of the CNG conversion kits for different vehicle's engine would seek public intention towards the use of NGVs. Besides that, the other barriers for NGV's market penetration are vehicle availability, after-market conversion, refuelling stations, and government policies [10, 11].

In Malaysia, most of NGVs are converted into either mono-fuel or bi-fuel system; that are dominant by public transport service such as taxi. From Department of Road Transport Malaysia (JPJ), most NGVs for logistics vehicles use a mono-fuel system for their diesel engines. However, based on Malaysia's CNG infrastructure facilities, the dual fuel systems is the good option because its offer fuel flexibility where the engine can operates with 100% diesel if the CNG supply is not available [12]. In addition, typical diesel engine comes with common rail fuel injection system where possess great potential for diesel dual fuel (DDF) system due to its flexibility in controlling fuel injection for diesel fuel replacement.

1.2   Problem statement

The conversion kits or retrofitted kits for diesel dual fuel (DDF) systems are additional components installed to run dual fuels in diesel engine. It requires integration process to adopt the DDF components to the diesel engine. Even though no major modification is needed and is mostly add-on components, the configuration setup to operate the dual fuels requires accurate tuning process and it is challenging in order to ensure that the engine has comparable performance and stability. In addition, the exhaust emission aspect should take into account due to stringent emission regulation. For example, in United State, the conversion kits must comply with the Environmental Protection Agency (EPA) requirement to meet the standard emission regulation [13].

Normally, the tuning process for the DDF system involves fuel management setting to reduce the diesel fuel quantity and replace with the CNG fuel. The fuel management setting usually is based on the fuel quantity for both fuels. The CNG substitution rate is dependent on diesel engine installed with dual fuel systems. Therefore, the DDF systems installer uses additional instrumentations such as knock sensor and air-fuel ratio (AFR) sensor during the tuning process for measurement and monitoring purposes. Both inputs from these two sensors are used as the guidance for the DDF systems tuner to verify the dual fuel system operation limitation. This means that the dual fuel engine should have a similar air-fuel ratio compared to diesel mode without any knock event. The efficiency of this tuning method become questionable due to several aspects that might overlook during the tuning process such as actual engine performance, fuel consumption, exhaust emissions and its stability.

Furthermore, the conventional method for measuring engine stability is by observing several consecutive combustion pressures. Generally, the in-cylinder pressure sensor is implemented to measure the combustion pressure where it a suitable instrumentation to provide accurate information. Unfortunately, it is not a practical approach for commercial purpose since it is costly.

The Response Surface Methodology (RSM) has the capability to provide the relation between fuel substitution rate and engine output characteristics through its statistical approach. This approach may help DDF tuner to understand the characteristics of the engine installed with the dual fuel conversion kits. The design of experiment using RSM could provide an experimental technique for predicting the responses of engine performances, exhaust emissions, combustion patterns and combustion stability. In addition, these response characteristics can be presented graphically through its contour plot and response surface profile, which are useful for establishing responses values and operating condition as required. The modelling methodologies are capable to predict the untested conditions with significant accuracy as per reported by [14–16].

The functionality of the commercial knock sensor that provides knock detection indicator can be utilized to provide information regard to engine stability. However, the vibro-acoustic signal from the knock sensor has large variability due to different background noises comes from an engine. A statistical method can be introduced to eliminate the background noises and provides the vibration intensity index. Thus, it can display the distribution of the vibration intensity index that shows the stability of the engine.

1.3   Research questions

The research questions for this study as follows:

i.   What statistical approach can be utilized to overcome the high variability of the acoustic index data for combustion stability data in Response Surface Methodology (RSM) analysis?

ii.   What can be achieved by assessing the responses of designed experiments for predicting the engine's output characteristics, i.e. engine performance, exhaust

emissions, combustion patterns and combustion stability using RSM? In addition, how significant is the prediction models developed using RSM.

iii. What relationships can be established between fuel management and engine output characteristics for diesel-CNG dual fuel engine using RSM?

1.4   Objectives

The objectives of the research are as follows:

i. To propose a novel statistical approach for vibro-acoustic signal analysis method via the offline mode to overcome the high variability of the acoustic index data as the input for combustion stability analysis.

ii. To develop the significant prediction models of engine output characteristics using Response Surface Methodology (RSM) and validate through the confirmation test against the experimental values.

iii. To predict the relationship between fuel management and engine output characteristics of diesel-CNG dual fuel engine using RSM.

1.5   Scopes of study

The scopes of this research are as follows:

i. The investigation is based on diesel-CNG dual fuel system conversion kits (brand: GI GASITALY) is installed in Toyota Hilux 2.5L common rail direct injection diesel engine (engine model: 2KD-FTV) with no modification on the stock ECU.

ii. The study is focused on the fumigated CNG dual fuel system.

iii. The dual fuel set ratios are targeted at 10%, 20%, 30% and 40% of diesel replacement in term of mass ratio within the operating range of 1500 to 3500 rpm engine speeds.

iv. The steady-state dynamometer testing is considered for this study by using chassis dynamometer.

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